Proton recoil detector of fusion neutrons using natural diamond

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Diamond, with its high radiation damage resistance, is an attractive alternative to silicon for neutron measurements in next step fusion experiments. A 200-μm-thick type IIa natural diamond with Ti/Au contacts was tested at the LAMPF-WNR facility by time-of-flight neutron energy identification. The crystal, having a carrier lifetime of up to 1 ns, was arranged in a low-energy-resolution, high-sensitivity proton recoil telescope consisting of a polyethylene radiator and a low-energy-proton Teflon filter. This arrangement is similar to the triton burnup monitor of Croft *et al.* [Rev. Sci. Instrum. **64**, 1418 (1993)], where a silicon photodiode was used as a recoil proton detector. The observed sensitivity for 14 MeV neutrons (DT) is $(1.25\pm0.15)\times10^{-3}$ counts/neutron. However, a high contribution of neutron-induced events in the diamond, mainly carbon ($A=12$) recoils, was observed. A one-dimensional calculation for the detector response to carbon recoil and proton deposition is compared to the measurements. Poor energy resolution of the diamond detector precludes pulse height discrimination between direct 2.5 MeV neutrons events and proton events corresponding to 14 MeV neutrons. Therefore, an overall DT/DD neutron sensitivity ratio of only $\sim$6.5 is achieved. This value is much lower than the ratio of 540 reported by Croft *et al.* in their silicon ($A=28$) monitor.

I. INTRODUCTION

In present day fusion experiments, and especially in next step ignited experiments, there is a need to monitor the fusion burn with good spatial and temporal resolution. This need requires the development of radiation-resistant neutron detectors having high sensitivity for 14.1 MeV DT neutrons and good discrimination against 2.5 MeV DD neutrons. The high radiation hardness of diamond[1] makes these crystals an attractive active material for these measurements. Relying in the reaction $^{12}C(n,\alpha)^{9}Be$, ‘‘rare’’ extra-pure diamond crystals have been tested as fast neutron spectrometers with an inferred energy resolution lower than 2%.[2,3] However, these spectrometers have intrinsically low sensitivities, typically $(1–2)\times10^{-4}$ counts/neutron. In this article we analyze the use of a ‘‘typical’’ type IIa natural diamond as a triton burnup monitor. The diamond is arranged in a proton recoil telescope similar to that developed by Croft *et al.*,[4] with the diamond crystal replacing the silicon photodiode of Croft's telescope. In this arrangement a proton radiator is used to improve the sensitivity over that originating from direct interaction of neutrons with the atoms of the detector and a filter for low-energy protons is added to help in the discrimination against 2.5 MeV DD neutrons.

II. EXPERIMENTAL SETUP

A 200-μm-thick type IIa natural diamond was prepared by depositing Ti/Au electrical contacts on one side of its $\sim$12.5 mm^2 surface. The interdigitated contacts covered 1/3 of the active surface. Two chemical vapor deposition (CVD) diamonds were also prepared; however, their response to alpha particles was much poorer in terms of energy resolution than that of the natural diamond detector. These CVD diamonds were not studied further.

The diamond crystal is mounted on an *N*-type connector and arranged in a proton recoil telescope similar to that of Croft *et al.*[4] A 2-mm-thick polyethylene proton radiator and a 80-μm-thick Teflon proton filter are placed in front of the crystal, separated from it by a $\sim$6 mm air gap. Since the range of 14.1 MeV protons in polyethylene is $\sim$2.3 mm,[5] the radiator used produces close to a maximum amount of protons. On the other hand, the filter used is thick enough to stop the 2.5 MeV protons (range in Teflon of $\sim$64.5 μm[5]) while producing a minimum perturbation on the higher-energy proton flux. The air gap has a negligible effect on the bulk of the allowed protons. The Ti/Au electrical contacts on the diamond were on the side closer to the radiator and filter.

The assembled detector is placed in the broad-spectrum neutron beam (100 keV to 800 MeV) produced by the Los Alamos Meson Physics Facility (LAMPF) accelerator combined with the Weapons Neutron Research (WNR) target facility.[6] In this latter facility neutrons are produced by 250-ps-wide pulses of protons causing spallation of a tungsten target. The detector, located $\sim$19 m away from the spallation target, is directly connected to an EG&G 142A preamplifier whose output is transmitted by a $\sim$10-m-long RG-58 coaxial cable to an EG&G 474 timing filter amplifier. The conditioned and amplified signal is then fed to an EG&G 934 constant fraction discriminator to obtain a start trigger pulse for a Tennelec TC861A time-to-amplitude converter (TAC). The TAC stop trigger is obtained by delaying the LAMPF-WNR electrical reference signal $\sim$2 μs with an EG&G 416A gate-and-delay generator. The time-of-flight spectrum is finally registered by an EG&G 916 multichannel analyzer (MCA) board installed in an IBM-compatible PC. A -64 V bias is supplied to the detector through the 142 A preamplifier.

Each channel of the analyzer registers events associated with neutrons having a particular time of flight (TOF) from the spallation target (i.e., energy). The main sources of uncertainty in this TOF/energy association come from the time spread produced by the EG&G 934 discriminator and from

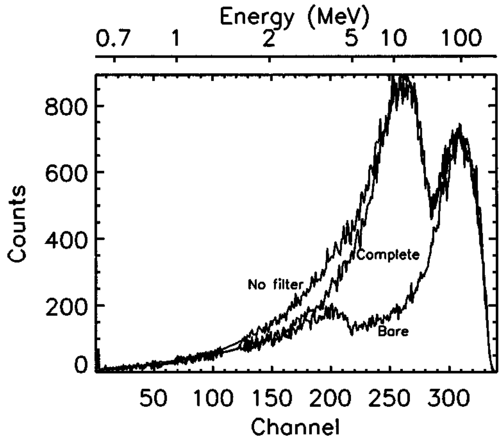

FIG. 1. Time-of-flight counts obtained in 3000 s acquisition runs on the LAMPF-WNR broad-spectrum neutron source. Shown are the results from the complete detector, the bare detector and the detector with no Teflon filter.

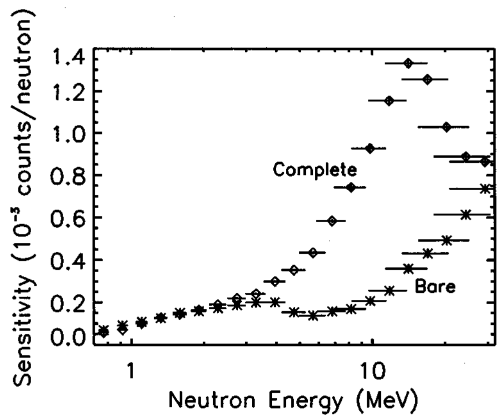

FIG. 2. Measured sensitivities (counts divided by the incident neutron spectrum) corresponding to the complete detector and the bare detector.

the calibration of a particular TOF with a particular neutron energy. (The LAMPF-WNR electrical reference signal has a fixed but unknown delay respect to the proton pulse striking the spallation target.) No identifiable gamma flash is observed in the measured TOF spectra shown in Fig. 1. The TOF-to-energy calibration used comes from identifying the dip in the bare detector response (described in the next section) with the threshold for neutron-induced inelastic carbon recoils. It is assumed in the analysis presented in this article that the WNR facility is sufficiently well collimated and shielded such that no spurious higher-energy events are registered delayed in time by the multichannel analyzer. Examples of such spurious events would be those caused by high-energy multiply-scattered neutrons that reach the detector after some delay. Support for this assumption comes from measurements of the byproducts of the reaction $^{10}B(n,\alpha\gamma)^{7}Be$, with the boron sample placed on and off the neutron beam.[7] The counts observed with the sample outside the beam were in all cases less than 1% smaller than those obtained with the sample placed on the beam.

III. RESULTS

Three 3000 s acquisition runs were obtained with the complete detector (i.e., diamond, radiator, and filter), with the diamond alone (''bare'' detector), and with the diamond and radiator but no filter. The results for these three runs can be seen in Fig. 1. The discriminator (EG&G 934) was set to a level corresponding to approximately 0.4 MeV alpha particles, inferred by irradiating the bare detector with the same amplifier and bias voltage but in normal pulse height counting mode with 5.8 MeV ^{244}Cm alphas.

As can be seen in Fig. 1, there is a substantial contribution from direct neutron events in the diamond (see the signal from the bare detector). In fact, with the complete detector essentially all counts observed around 2.5 MeV correspond to direct neutron events. The protons that originate in the radiator by recoil collisions with 2.5 MeV neutrons are effectively stopped by the Teflon filter. In the low-energy range ($\leqslant 1$ MeV), the 6 mm air gap between the radiator and the diamond is enough to nearly stop all protons or at least reduce their energy below the discriminator level. At very high energies ($\geqslant 80$ MeV) the proton-recoil cross section in the polyethylene radiator is small enough that the counts are dominated by direct neutron events and possibly some charged particle events originating at high energy outside the detector. The drop in the bare detector trace around channel 215 (~ 4.9 MeV) corresponds to the threshold above which neutron-induced inelastic carbon recoils in the diamond become possible. Above this incident energy some of the interaction energy is absorbed by the carbon nucleus with a gamma eventually emitted. This gamma is not detected by the diamond, and consequently the total electrical pulse generated in the diamond is reduced below the discriminator level and the apparent count rate reduced.

The traces in Fig. 1 can be compared with the number of neutrons incident on the detector during the time of measurement. This neutron flux is calculated with a transport code combined with the Intra-Nuclear-Cascade model developed at Los Alamos.[8] The results of the comparison can be seen in Fig. 2. A sensitivity of $(1.25\pm 0.15)\times 10^{-3}$ counts/neutron is obtained for 14.1 MeV DT neutrons together with a sensitivity ratio of approximately 6.5 between the DT neutrons and 2.5 MeV DD neutrons. This is a substantial improvement over the values corresponding to the bare detector which, leaving aside possible external charged particle effects (see the next section), are $(3.5\pm 1.0)\times 10^{-4}$ counts/neutron and a discrimination ratio of around 2. Nevertheless, the sensitivity ratio observed with the complete detector is much lower than the ratio of 540 reported by Croft *et al.*[4] in their silicon monitor.

IV. DISCUSSION

In order to analyze the response characteristics of the detector, the measured sensitivities can be compared with calculations that take into account the neutron reaction cross sections, the proton energy deposition rates, and the detector geometry. Results from these comparisons can be seen in Figs. 3 and 4 for the bare detector and complete detectors, respectively. Due to the small number of random variables allowed in the model used for these calculation, it is possible

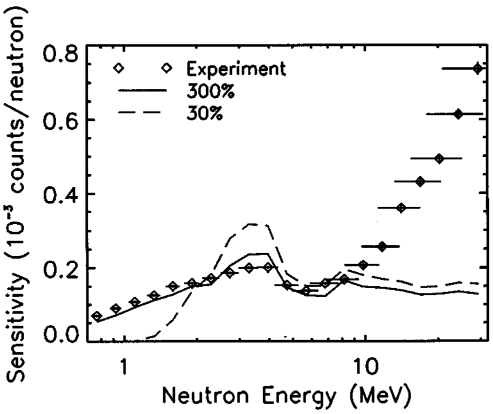

FIG. 3. Comparison of the bare detector results with two numerical calculations of the detector response (energy resolutions of 30% and 300%).

to evaluate the probabilities for different energy depositions in the diamond for each incoming neutron. Given then a discriminator energy level and a energy resolution value, the probability for obtaining an electric pulse above discriminator threshold can be evaluated. The cross sections used in these calculations are those from the ENDF library and the energy deposition rates are from Ref. 5.

The calculation for the bare detector (Fig. 3) utilizes only elastic $^{12}C(n,n)^{12}C$ collisions, inelastic $^{12}C(n,n)^{12}C^*$ reactions to the first excited carbon level, and $^{12}C(n,\alpha)^9Be$ reactions, since all other reactions have substantially lower cross sections. Figure 4 shows the comparison of the ''proton'' contribution of the complete detector, that is, the difference between the responses of the complete detector and the bare detector. The calculation in this case employs elastic-recoil collision cross sections in the polyethylene radiator to generate the proton flux. Once this flux has been created the calculation follows the energy decay of this flux as it transverses the remaining portion of radiator, the complete Teflon filter and the air gap and, if the protons are not stopped in either of these layers, calculates the energy deposited in the diamond (carbon). All layers, including the diamond, are considered one dimensional and the protons travel in straight lines through them. The effects of the electrodes (2000-Å-thick gold and 500-Å-thick Ti) on the energy decay of the protons is neglected. The electrodes are only included in the calculation to account for the fact that below them the electric field is negligible and no induced charge is measured from carriers produced in these regions.

The finite observed sensitivity to low-energy (0.7–2.0 MeV) neutrons of the bare detector is difficult to reconcile with the amount of energy needed to be deposited to exceed the discriminator setting. The elastic energy transfer from a neutron to a recoiling carbon nucleus should provide only a fraction of this incident energy into the diamond. In order to explain the long low-energy tail one needs to argue that the energy resolution of our diamond detector to carbon recoils from neutron interactions is substantially poorer than the ~30% energy resolution observed with the 5.8 MeV ^{244}Cm alpha particles, as poor as 300%!. With this high-energy resolution value, a reasonable agreement between the bare detector results and the numerical calculation (Fig. 3) for neutron energies lower than 10 MeV can be obtained by considering the diamond to have an effective thickness of 24 μm. This effective thickness is within 5% of that expected from the electrode geometry and the applied bias. While different values for the effective thickness proportionally modify the calculated sensitivity for all neutron energies, the energy resolution value affects predominantly the sensitivity in the low-energy tail (0.7–2.0 MeV). Calculations with better energy resolutions (the dashed curves in Figs. 3 and 4) result in lower sensitivities of the bare detector in this energy range than those measured. This choice of effective thickness and resolution produces also a good agreement between the ''proton'' contribution results and the corresponding calculation (Fig. 4) in the same energy range. It is assumed here that the discriminator energy level employed during the neutron measurements is the same as that inferred for alpha particles, i.e., 0.4 MeV.

The source of the discrepancy in both Figs. 3 and 4 for energies greater than 10 MeV is also not known. One possible explanation is that at higher energies the effective thickness for neutron-induced events in the diamond may be bigger than that estimated for lower energies. At high neutron energies, more carriers are produced in each event and hence there is a higher probability of inducing an electric pulse above the discriminator level from regions of low electric fields (i.e., beyond the 24 μm). In this way, the discrepancy observed in Fig. 3 is reduced. This conjecture, although favorable for the bare detector results in the sense that reduces the discrepancy observed, does not apply for proton ionization in the diamond. On the contrary, above 10 MeV the proton energy deposition (or ionization) rate in diamond decreases as the energy of the proton increases. So, another explanation is needed for the complete detector comparison.

A second explanation for the mismatch at high energies is that in this energy range the bare detector is sensitive to charged particles originating in the surrounding structures of the WNR facility and hence additional counts are observed over those expected. On the contrary, the complete detector is not sensitive due to the presence of ''filtering'' layers. The mismatch in Fig. 4 is then due to the fact that the proton

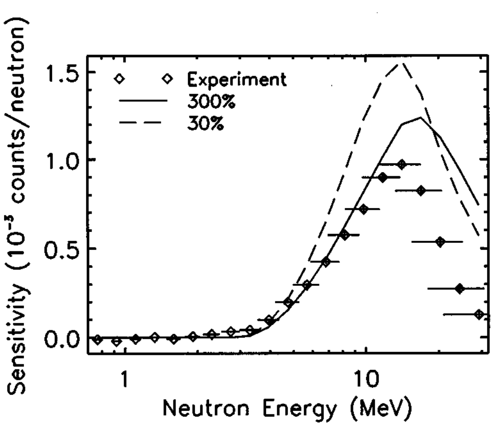

FIG. 4. Comparison of the results corresponding to the ''proton'' contribution of the complete detector with two numerical calculations of the detector response response (energy resolutions of 30% and 300%).

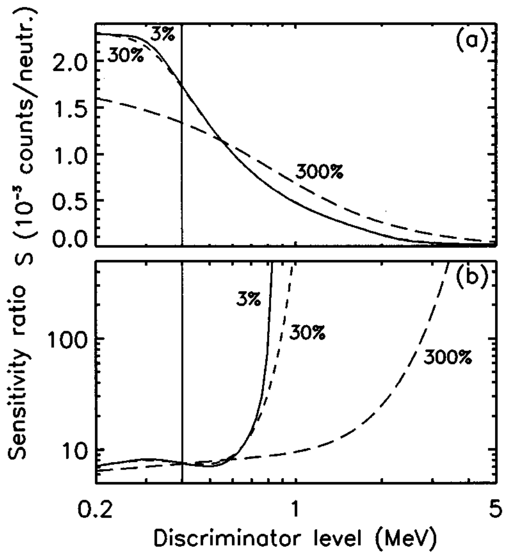

FIG. 5. (a) Calculated complete detector sensitivity (S) for 14.1 MeV DT neutrons and (b) sensitivity ratio between DT neutrons and 2.5 MeV DD neutrons as a function of discriminator energy level. The detector is assumed to have an effective thickness of 24 μm. Three different energy resolutions are shown: 3%, 30%, and 300%. A vertical line is drawn at the discriminator level used in the experiment.

contribution plotted has been obtained by subtracting the additional ''charged-particle'' counts which are not actually present in the complete detector. The amount of additional counts observed in Fig. 3 is strikingly similar to the amount of missing counts observed in Fig. 4. It should be emphasized that these charged particles, if present, do not affect the measurements with the complete detector below 15 MeV due to the presence of the 2 mm of polyethylene and 80 μm of Teflon. At the same time, in terms of charged particles created by neutrons in the detector housing, the good fit observed at low energies indicates that their contribution is negligible.

The poor energy resolution of the detector precludes pulse height discrimination between 2.5 MeV neutron events and events corresponding to 14 MeV neutrons. Figure 5 shows the calculated complete detector sensitivity for DT neutrons and the sensitivity ratio between DT neutrons and DD neutrons as a function of discriminator energy level. It is assumed that the detector has an effective thickness of 24 μm and three different energy resolutions are considered: 3%, 30%, and 300%. As can be seen in this figure, for a poor resolution detector (300%) good discrimination can be obtained only at the expense of a severe drop in the sensitivity for DT neutrons. On the other hand, a good resolution detector (including 30% as a good one) could obtain a reasonable discrimination ratio with only a moderate sacrifice on the sensitivity. Nevertheless, since the active material is carbon (diamond) with atomic mass of 12, the sensitivity ratio in these detectors is inherently lower than that of silicon detectors (atomic mass of 28) such as that of Croft *et al.*[4] The lower the atomic mass, the higher the energy acquired by the recoiling nucleus in a collision with an incoming neutron and hence, the higher the pulse height observed. Experimental runs with poor statistics were tried at higher discriminator levels (up to 1.1 MeV), with the low-energy counts still existing. Nevertheless, the poor statistics in these runs do not allow further discussion about the origin of the low-energy tail observed. Further measurements may be planned for the near future to quantify better the energy resolution of the detector.

V. CONCLUSIONS

We have measured the neutron sensitivity of a proton recoil detector using natural type IIa diamond on the LAMPF-WNR beam, and compared the measurements to a 1D calculation. The observed sensitivity for DT neutrons in the diamond detector analyzed is comparable to that of the silicon detector of Croft *et al.*[4] and may be of interest for the fusion community. Nevertheless, the poor energy resolution ($\geqslant$30%) of this diamond detector precludes pulse height discrimination between 2.5 MeV DD neutron events and 14 MeV DT events yielding a low overall DT/DD neutron sensitivity ratio. This ratio would increase in diamond detectors with better resolutions ($<$30%) and an appropriate choice of discriminator level, although some degradation in the DT neutron sensitivity is inevitable.

ACKNOWLEDGMENTS

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